1D simulations of the Helicon Double Layer

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Marco Manente*
CISAS University of Padua, Padova Italy
Johan Carlsson†
Tech-X Corporation, Boulder, Colorado, USA
Ivano Musso‡
CISAS University of Padua, Padova Italy - ISTI-CNR Pisa Italy
Cristina Bramanti§
Advanced Concept Team ESA ESTEC Noordwijk - The Netherlands
Cinzia Giacomuzzo,¶ and Daniele Pavarin,‖
CISAS University of Padua, Padova Italy

Abstract: Double-layers (DLs) are electrostatic structures able to support a potential jump in a narrow spatial region of plasmas. Recently some laboratories have reported about a current-free DL obtained by a helicon-source plasma expansion along a diverging magnetic field. Their findings can lead eventually to development of innovative space propulsion system. Experiment has shown evidence of DL in case of floating boundary conditions and biased boundary conditions. To study DL Layer formation and stability and its application to spacecraft thruster a new 1-D PIC code has been developed and implemented. The new algorithm solves for the Boltzmann density parameter and, in case of a Neumann (floating) boundary condition, the surface charge density simultaneously as it solves for the discretized electrostatic potential. Stability is demonstrated for timesteps exceeding the electron plasma period.

Nomenclature

B = Magnetic field
e = electron charge
m = particle mass
n = plasma density
n_e = electron density
r = radius of magnetic lines tube
T = particle temperature
T_e = electron temperature
z = position
μ = adiabatically invariant magnetic moment
σ = surface charge density
ϕ = potential

*Post-Doc Fellow, Department of Mechanical Engineering, University of Padua, Via Venezia 15 35131 Padova Italy
†Research Scientist, Tech-X Corporation, 5621 Arapahoe Ave Suite A, Boulder, CO 80303, USA
‡PhD student, Department of Mechanical Engineering, University of Padua, Via Venezia 15 35131 Padova Italy - ISTI-CNR Pisa Italy
§Research Fellow, Advanced Concept Team ESTEC - DG-PI, Keplerlaan 1 - 2201 AZ Noordwijk - The Netherlands
¶Post-Doc Fellow, Department of Mechanical Engineering, University of Padua, Via Venezia 15 35131 Padova Italy
‖Researcher, Department of Mechanical Engineering, University of Padua, Via Venezia 15 35131 Padova Italy

I. Introduction

THIS paper describes the 1D simulations of Double layer performed with a new implicitly charge-conserving solver for Boltzmann electrons. Recently some laboratories[1–5] have reported about a current-free Double Layer obtained by a helicon-source plasma expansion along a diverging magnetic field. Their findings can lead eventually to development of innovative space propulsion system.[6] Although considerable progress has been made, at the present time a number of aspects related to this phenomenon are still only partially understood.[7]

Double Layer plasma thruster represents the latest innovation in the propulsion field. It is based on an helicon RF plasma source surrounded by a magnetic coil which generates a magnetic field which confines plasmas in the source and drive plasmas outside of it as in a magnetic nozzle. Plasmas acceleration happens through a Double Layer which forms at the exit of the source as explained in the following. Double layer plasma thruster are much simpler than VASIMR type engine since doesn't apply ICRH, however high specific impulse relays on Double layer formation shape and stability. This is the main reason why a detailed model of the plasma behavior inside of the source and at the exit off it is required. In the following it is provided a description of the numerical model developed and implemented.

II. PPDL code

The goal of the simulation is to verify the presence of a potential drop observed under certain conditions in an expanding magnetic field downstream from a helicon plasma source. The relevant geometry is cylindrical with azimuthal symmetry.

In many cases full particle-in-cell (PIC) simulation[8] can be impractical due to the need to resolve the fast electron time scales and short length scales to avoid numerical instability. Hybrid schemes with kinetic ions but Boltzmann electrons, i.e. inertialess electrons in instantaneous thermodynamic equilibrium, allow larger time steps before numerical instability occurs.

The main feature of PPDL are listed in the following:

- Drift-kinetic ions, where the magnetic moment is assumed to be an adiabatic invariant. The drift kinetic equation of motion
- The expansion of the magnetic field is considered
- Boltzmann electrons, assuming Maxwellian distribution and inertialess.
- Floating boundary conditions.
- Plasma generation is simulated through a source term.

The advantage of Boltzmann electrons is that electron time scale (plasma and gyro periods) do not have to be resolved, but on the other side it requires a non-linear Poisson solver to determine the electrostatic potential. With the hybrid Boltzmann electron/drift-kinetic ion approach, the time step is only limited by ion period which is two orders of magnitude larger than electron plasma period and ion gyro period, which can become very short in a strong magnetic field. Our implicit treatment of the Boltzmann density parameter and surface charge density guarantees charge conservation, which is necessary for numerical stability, while keeping the Jacobian sparse. The all-implicit algorithm is implemented for a quasi-two-dimensional cylindrical geometry with drift-kinetic ions, suitable for certain plasma thruster simulations.

Three equations are added to the system of the discretized Poisson equation. The first one describes charge conservation in the simulated plasma, the second one corresponds to a Neumann boundary condition and the third one is for charge conservation on the boundary with floating potential. The extra equations allow us to solve simultaneously for the electrostatic potential, the Boltzmann density parameter and the surface charge on the floating-potential boundary, rather than evolving the latter two outside of the solver.

Thus, PPDL is very fast and efficient and still capable of simulating the relevant physics. To better fit the experimental set-up the presence of magnetic field is simulated by the analytic solution of a field generated by one or more solenoids. The gradient of the magnetic field is also calculated analytically and used for adding the ∇B velocity to the drift-kinetic ions. The dilution of the charge density due to the expanding magnetic field has also been incorporated into the non linear Poisson solver.

A. Magnetic field

The magnetic field is calculated, knowing the solenoid configuration, by the superposition of the magnetic field generated by a single loop.

We consider a plasma of radius r_0, density n_0, and temperature T_e created in a uniform field B_0 and then injected into a region of expanding field lines. For plasma frozen to the field lines.

The expansion of $B(z)$ and $n(z)$ plasmas along the magnetic field is also simulated using the relation

$$\frac{n}{n_0} = \frac{B}{B_0} = \left(\frac{r_0}{r}\right)^2 \tag{1}$$

where $r(z)$ is the radius of magnetic lines at position z.

B. Algorithm

In the Boltzmann approximation the electron density is given by

$$n_e(\mathbf{x}) = n_0 \exp\left(\phi(\mathbf{x})/T_e\right) , \tag{2}$$

where ϕ is the electrostatic potential, T_e is the electron temperature measured in eV and n_0 is the Boltzmann density parameter. With Boltzmann electrons the Poisson equation becomes nonlinear because the electrostatic potential ϕ depends on the charge density ρ, which through Eq. (2) exponentially depends on ϕ. In the presence of sources or sinks, the density parameter n_0 will change over time and, if it is not done self-consistently with ϕ, electron charge will not be conserved. When a plasma is in contact with a material wall n_0 will in general be reduced by the electron flux from the plasma to the wall.

For the application of primary interest to us the boundary conditions for the nonlinear Poisson equation are Dirichlet/Neumann (prescribed ϕ and prescribed $\nabla\phi$, respectively), rather than the pure Dirichlet of Cartwright.[9] More specifically the Neumann condition is for a wall with floating potential, where the lost electrons and ions build up a net surface charge that determines the normal component of the electric field $-\nabla\phi$. To make the nonlinear Poisson solve robust in this case we had to calculate n_0 and the surface charge density σ fully self-consistently with ϕ. We do this by extending the nonlinear system of equations given by the discretized Poisson equation with equations for the conservation of charge in the plasma and on the floating-potential wall, respectively.

C. Collisions

A Monte-Carlo algorithm is used to simulate elastic collisions between ions and neutrals. With drift-kinetic ions the velocity coordinates are $v_z, v_\perp = \sqrt{2\mu B/m}$, where μ is the adiabatically invariant magnetic moment, B is the magnetic field strength and m is the ion mass. The probability for a collision during a time step Δ_t is $n_n Q(v) v \Delta_t$, where n_n is the neutral density, Q is the cross section and v is the ion speed, $v^2 = v_z^2 + v_\perp^2$. For each ion macroparticle during each time step a random number ζ, uniform in the interval $[0, 1)$, is generated. If the random number is smaller than the collision probability, the velocity coordinates of the macroparticle are changed according to the type of collision.

For collisions between Ar^+ and Ar we use the cross sections suggested by Phelps,[10] who divides the total cross section into $Q(\epsilon_i) = Q_i(\epsilon_i) + Q_b(\epsilon_i)$, where ϵ_i is the initial ion kinetic energy in the center-of-mass frame, Q_i is the cross section for isotropic scattering and Q_b for back scattering. The formulas given by Phelps are:

$$Q_i(\epsilon_i) = \frac{2 \cdot 10^{-19}}{\epsilon_i^{0.5}(1+\epsilon_i)} + \frac{3 \cdot 10^{-19}\epsilon_i}{(1+\epsilon_i/3)^{2.3}}$$

and $Q_b = (Q_m - Q_i)/2$, with

$$Q_m(\epsilon_i) = 1.15 \cdot 10^{-18} \epsilon_i^{-0.1} (1 + 0.015/\epsilon_i)^{0.6} .$$

If an isotropic (in the center-of-mass fram) collision occurs, the angle $\theta = \arctan(v_\perp/v_z)$ is calculated and the transformation

$$v_z \to (v_z + v\cos(\theta + \delta\theta))/2 ,$$
$$v_\perp \to (v_\perp + v\sin(\theta + \delta\theta))/2 ,$$

where $\delta\theta = 2\pi\zeta$, is performed. If a back scattering (in center-of-mass frame) takes place, the corresponding transformation is simply $(v_z, v_\perp) \rightarrow (0, 0)$. The post-collision magnetic moment is finally calculated by $\mu = \frac{mv_\perp^2}{2B}$.

III. PPDL results

The monodimensional code PPDL was performed with several conditions and geometries[11] for thrusters to identify the critical parameters. It uses the source modeled in the previous step and studies the expansion of the system. The results are summarized in the follow (all values are in S.I except temperature in eV): the model is similar to Charles experiment, with different boundary condition: the right boundary can be floating so the system is sometime mirrored to permit to obtain the floating wall near the source or far from the source. In some simulations we observed an ion beam velocity around 1.4 times the ion Bohm velocity

Time step stability

The test simulations performed for the implicitly non-linear Boltzmann solver show that the algorithms is stable for large time step, more than twice the plasma period also for the Dirichlet-Neumann problem

Temperatures

Ion and electron temperatures

Obviously the maximum potential is increased by the temperature due to sheath effect: as shown in the Figure 1.

The ratio between ΔV and V_{max} increase with V_{max}, so it seems that some advantage can derive increasing the temperature. A larger difference between electron and ion temperature increases the potential drop as in Figure 2, where we use $T_e = T_i$ =60 eV (`MAlongtime3`)and T_e=60 eV T_i=1 eV (`MAlongtime7`).

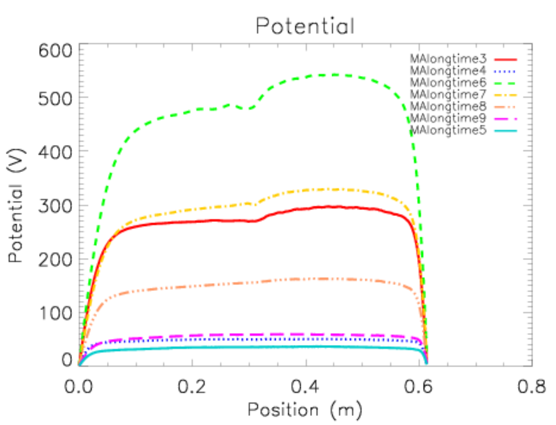

Figure 1. Potential as function of the position at different ion and electron temperatures: `MAlongtime3`: **T_e=T_i=60 eV** `MAlongtime4`: **T_e=10 T_i=10 eV** `MAlongtime6`: **T_e=100 T_i=1 eV** `MAlongtime7`: **T_e=60 T_i=1 eV** `MAlongtime8`: **T_e=30 T_i=1 eV** `MAlongtime9`: **T_e=10 T_i=1 eV** `MAlongtime5`: **T_e=6 T_i=.1 eV**

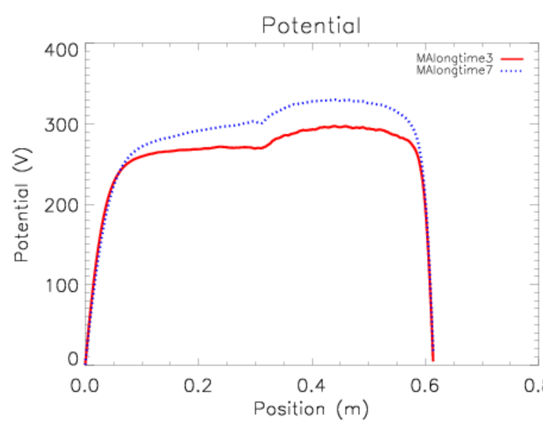

Figure 2. Potential as function of the position at different ion and electron temperatures: `MAlongtime3`: **T_e=T_i=60 eV and** `MAlongtime7`: **T_e=60eV T_i=1 eV.**

Magnetic field

Coil configuration

We used two different configurations of magnetic field: the first one uses line without inversion, with a long solenoid also in the expansion camera as shown in Figure 3.

The second one uses two solenoid only over the source as shown in figure 4.

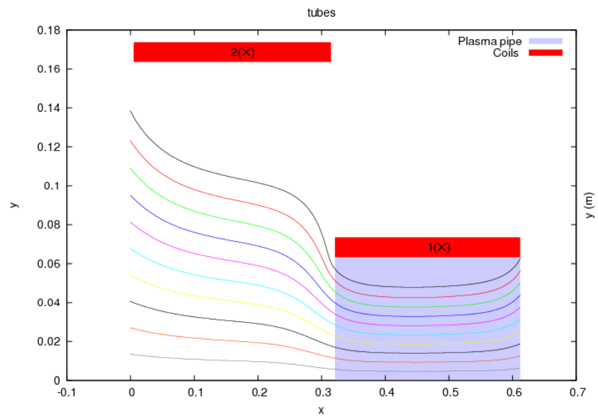

Figure 3. Magnetic field lines with solenoid in expansion chamber

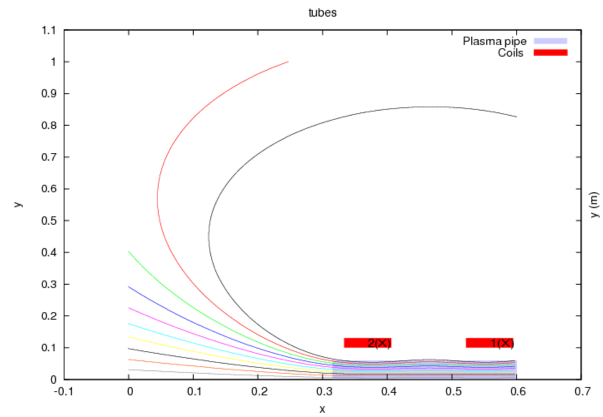

Figure 4. Magnetic field lines with two solenoid only over the source

We use a plasma frozen to the magnetic lines, in order to use only the magnetic lines that do not turn. PPDL uses the first of the magnetic tube that does not invert: in that case we can define the radius of the larger close magnetic tube for each z and we can calculate the density dilution with eq. 1

Magnetic field strength

There's no significant difference if we simply increase the wire current to achieve a different magnetic field strenght, from B_{max}=0.015T to B_{max}=0.03T

Plasma source

Source position

The position of source rate is very important for the localization of potential drop as shown in figure 5 where the `CIxcomp_invpd14` has the source in the original position (0.35-0.55 m), `CIxcomp_invpd15` has the source between 0.45 to 0.55 m and `Cixcomp_invpd16` between 0.35 to 0.45 m.

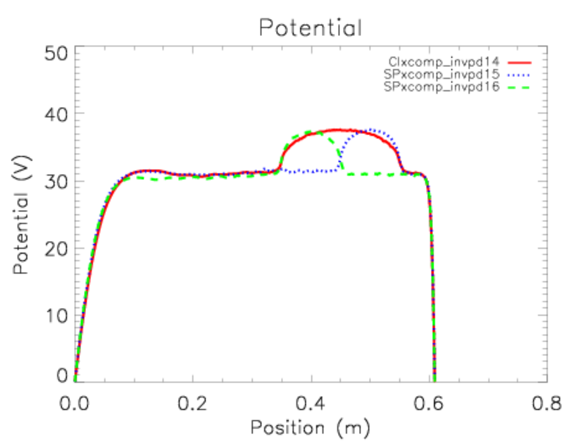

Figure 5. Potential profile for different length and position of the plasma source

Neutral pressure

The elastic collision probability between ions and neutrals, calculated with the method explained above, shows no collisions for pressure around 0.1-3 mTorr (so there is no influence of neutral by collisions). The neutral pressure shows influence with XOOPIC simulations[11] so probably the considered elastic ion-neutral collisions are negligible compared with the electrons collisions.

Density

From the comparison of the same simulations with different plasma density we can see that the influence of density is not important for the potential drop as in figure 6 and 7. All the curves in Figure 6 are different simulations at the same density. The same potential profile is plotted in Figure 7 at different densities.

The density can influence the kinetic energy for the detachment

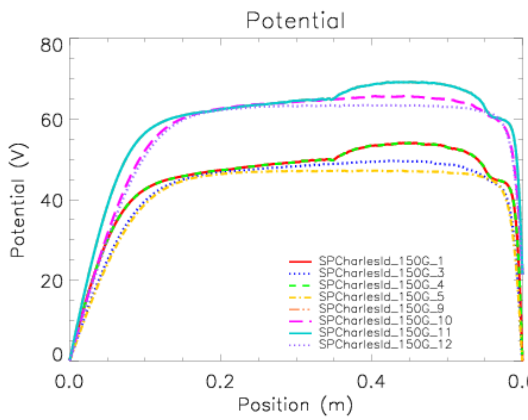

Figure 6. Potential profile of several simulation: all simulations present density = 10^{14}

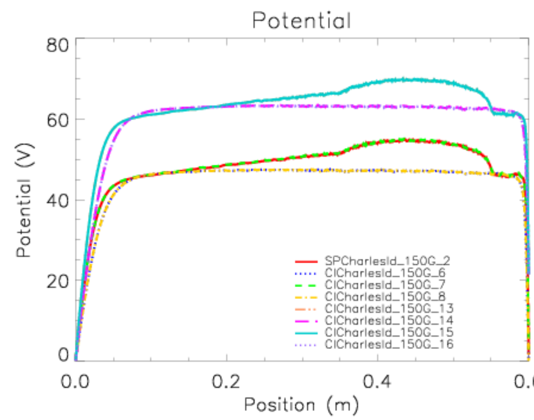

Figure 7. Potential profile of several simulation: all simulations present density = 10^{15}

DC bias

The influence of DC bias is only related to the value of maximum potential as shown in Figure 8 but the potential drop is practically unaffected In Figure 9 the lower curves (`SPESA_Bosdld4` SR=5e18 and `CIESA_Bosdld13` SR = Mant.) are at DC bias 0V-0V. The upper curves (`SPESA_Bosdld5` SR=5e18 and `CIESA_Bosdld14` SR = Mant.) are at DC bias 10V-0V (In the simulation the source rate that maintain the constant density inside the system is called `Mant.` Every particle that go out of the system at wall is replaced inside the source)

Gas

The influence of the propellant on the potential drop has been analysed. Hydrogen and Argon were simulated as propellants. Argon shows a maximum potential higher than hydrogen, as shown in Figure 10, but the ΔV is similar. The specific impulse reached by argon and hydrogen is around 650s and 3800 s respectively.

Time stability

The time stability of potential drop is presented in Figure 11 for a time length of 1 ms. The graph shows the potential profile time history, and it is possible to see that the profile remains constant for all the time after a short transient period.

System Length

No effect of the system length has been observed as appears from in Figure 12.

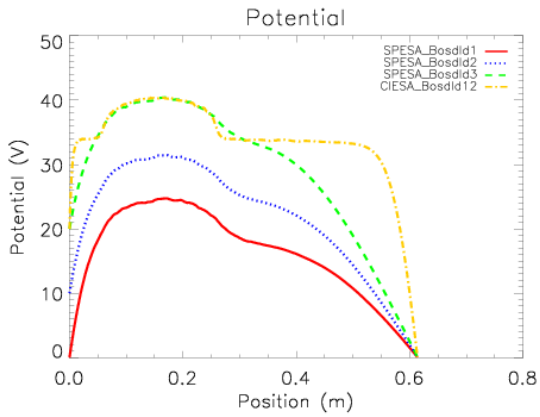

Figure 8. Dc Bias influence:`SPESA_Bosdld1` **(Dc bias 0V)** `SPESA_Bosdld1` **(Dcbias 10V)** `SPESA_Bosdld1` **(Dc bias 20V)** `CIESA_Bosdld12` **(Dc bias 20V and SR = Mant.)**

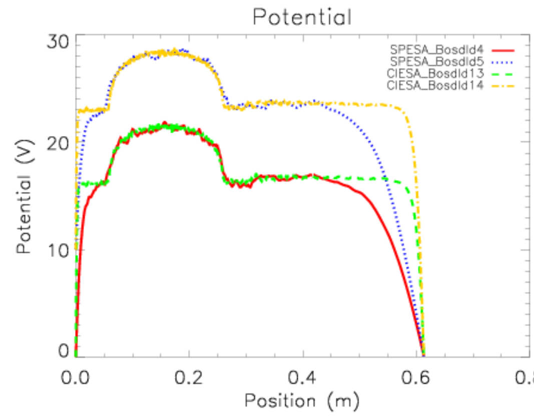

Figure 9. DC bias influence: The lower curves (`SPESA_Bosdld4` **SR=5e18 and** `CIESA_Bosdld13` **SR =Mant.) are at 0V-0V DC bias. The upper curves (**`SPESA_Bosdld5` **SR=5e18 and** `CIESA_Bosdld14` **SR = Mant.) are at 10V-0V Dcbias**

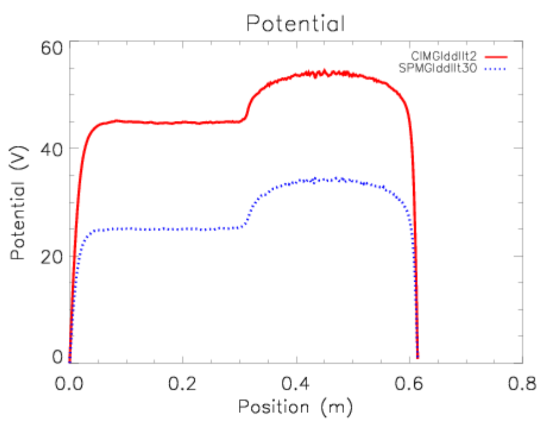

Figure 10. comparison between Argon (`CIMGlddllt2`**) and Hydrogen (**`SPMGlddllt30`**)**

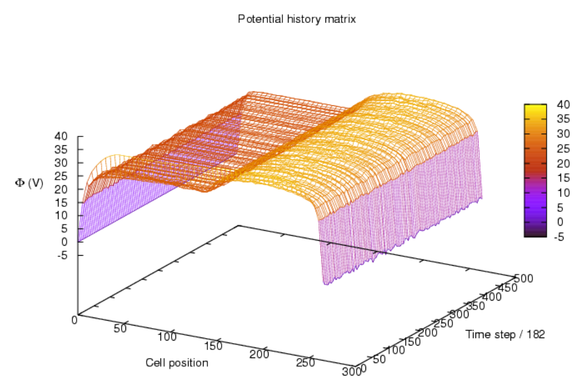

Figure 11. Time history of potential profile

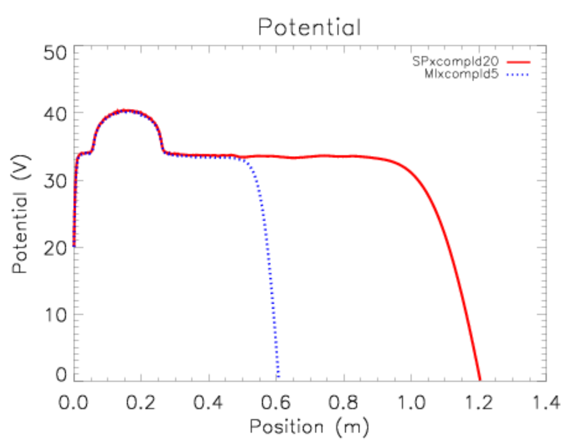

Figure 12. Same simulation with different system length

IV. Conclusions

The models gives a good description of the physics of the thruster: this makes it possible to simulate the plasma behaviour in the desired configuration and to determine the efficiency and thrust performance. The monodimensional code PPDL is also stable with time step more than twice the plasma period

Acknowledgments

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